XIV International Conference on Beauty, Charm and Hyperon Hadrons

Direct *CP* violation in charm mesons at LHCb

Cracow, 6 June 2022

Artur Ukleja on behalf of the LHCb experiment
(a charmer at National Centre for Nuclear Research)

Menu

- **Introduction**
  - ✧ Why are we interested in charm physics?
  - ✧ Known sources of *CP* violation in the Standard Model
  - ✧ Charm meson decays where *CP* violation can appear

- **The examples of time integrated measurements in charm meson decays**
  - ✧ *CP* violation in $D^0 \to K^0_s K^0_s$
  - ✧ *CP* violation in $D^+_{(s)} \to h^+\pi^0$, $h^+\eta$
  - ✧ *CP* violation in $D^\pm_{(s)} \to \eta^{(')} \pi^\pm$
  - ✧ *CP* violation in very rare $D^0 \to h^+h^- \mu^+\mu^-$

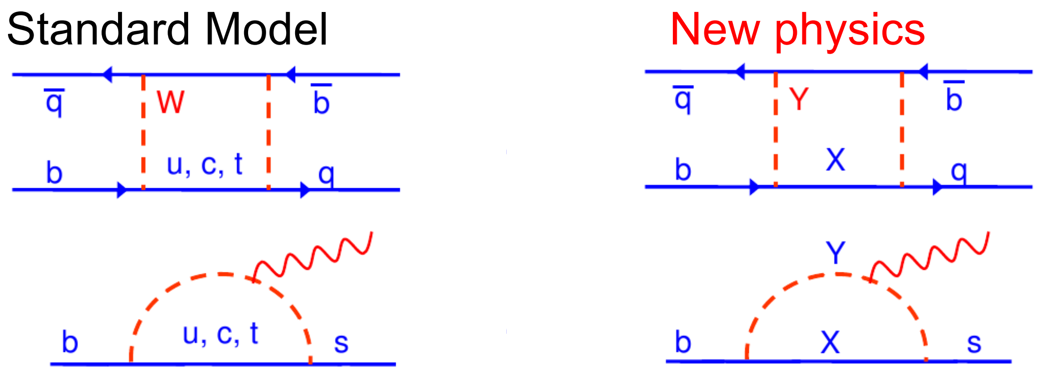
- **Summary**

Why are we interested in charm physics?

- In the Standard Model (SM), the known value of *CP* violation (CPV) is too small to explain the observed size of matter domination over antimatter in the universe

- At LHCb, we very precisely test known CPV in the SM
  → finding disagreement will be indirect indication of new phenomena existence

- The new particles can appear in the loops


Standard Model

New physics

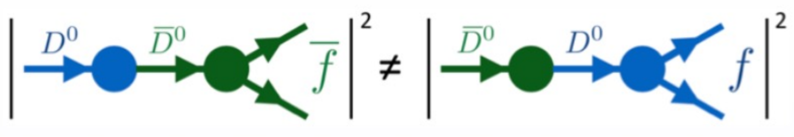
box diagrams

penguin diagrams

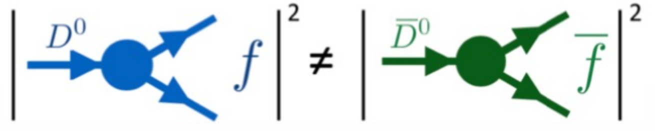
- Charm sector is very promising since the background from the SM is very small, expected CPV is only $\lesssim 10^{-4} - 10^{-3}$ (much smaller than we measure in beauty meson decays)

Three ways of *CP* violation in the Standard Model

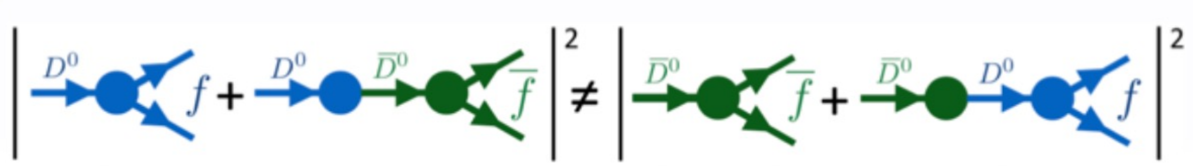
1. In the mixing (only neutral particles)
   $P^0 \rightarrow \text{anti-}P^0 \neq \text{anti-}P^0 \rightarrow P^0$

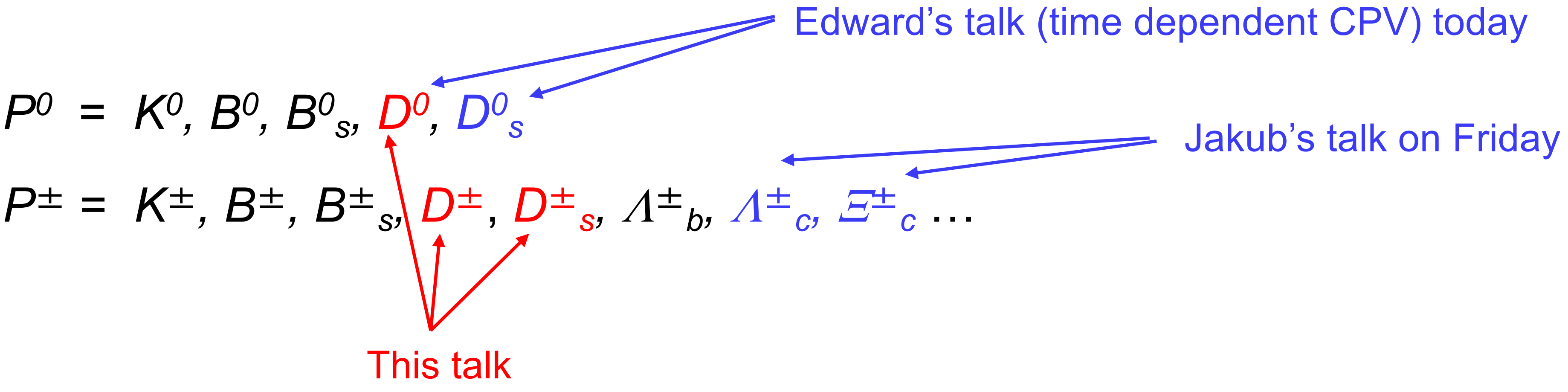


2. In the amplitudes of direct decays
   (neutral and charge particles)
   $P^\pm \rightarrow f \neq \text{anti-}P^\pm \rightarrow \text{anti-}f$



3. In the interference between
   direct decays and decays via
   mixing (only neutral particles)





Edward's talk (time dependent CPV) today

$P^0 = K^0, B^0, B^0_s, D^0, D^0_s$

Jakub's talk on Friday

$P^\pm = K^\pm, B^\pm, B^\pm_s, D^\pm, D^\pm_s, \Lambda^\pm_b, \Lambda^\pm_c, \Xi^\pm_c \ldots$

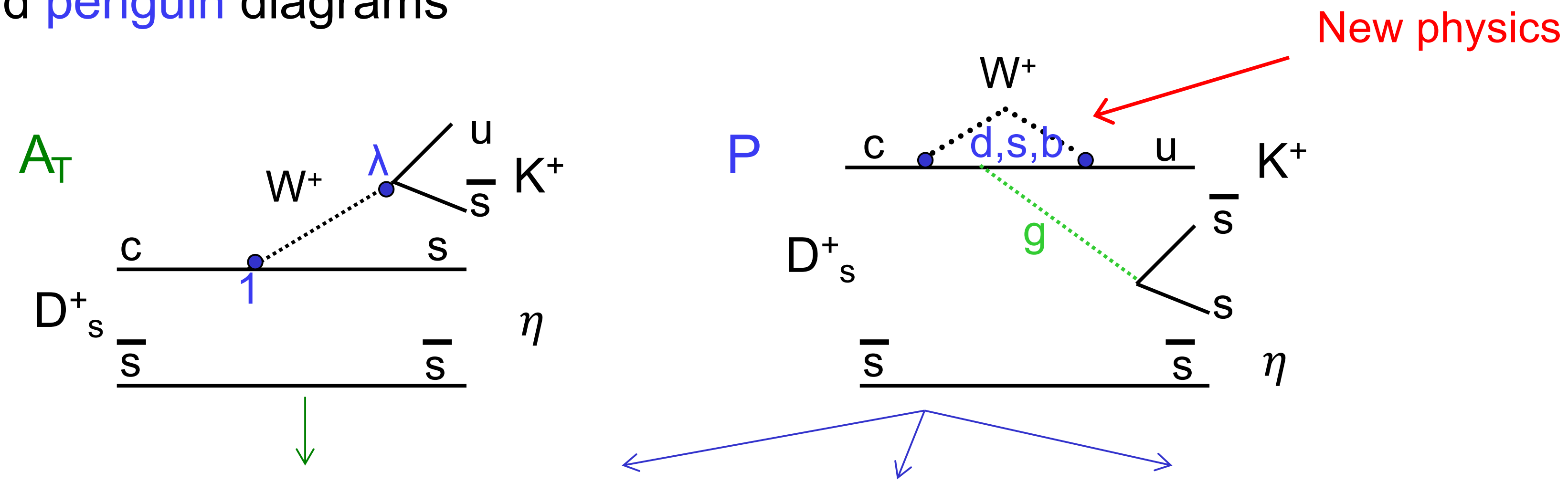
This talk

CP violation in direct decays

Singly Cabibbo−suppressed decays (SCS):

- the only place for *CP* violation in the Standard Model
- both: tree and penguin diagrams

$\lambda = 0.22$



$$A = \underset{\sim\lambda}{V_{us}V^*_{cs}}\, A_T + \underset{\sim\lambda}{V_{ud}V^*_{cd}}\, P_d + \underset{\sim\lambda}{V_{us}V^*_{cs}}\, P_s + \underset{\sim\lambda^6}{V_{ub}V^*_{cb}}\, P_b$$

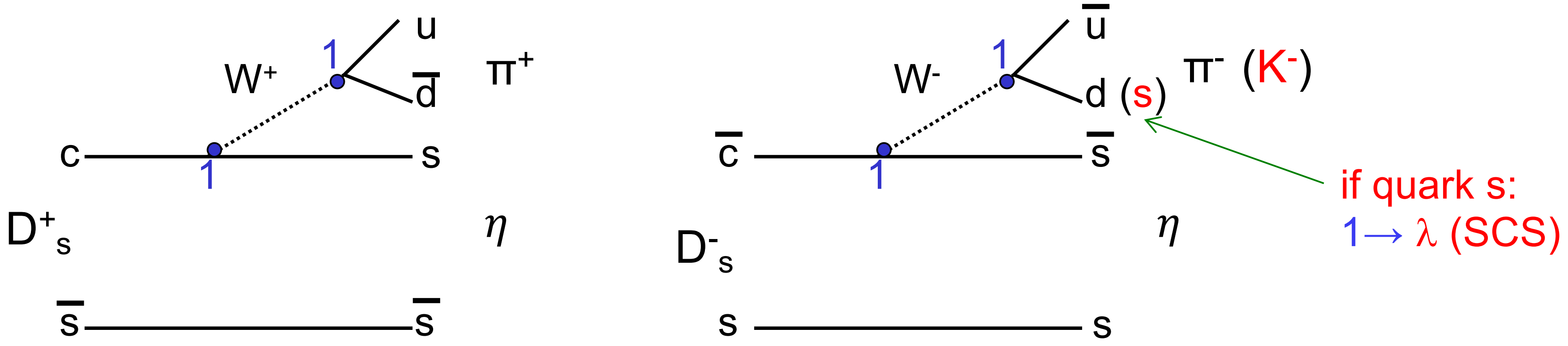
$$Asym_{CP} \sim \underset{=A_T}{|A_1|}\underset{=P}{|A_2|}\,\underset{\text{weak phases}}{sin(\phi_1 - \phi_2)}\,\underset{\text{strong phases !!!}}{sin(\delta_1 - \delta_2)}$$

To observe *CP* violation, at least two amplitudes must interfere with different weak phases AND DIFFERENT STRONG PHASES

Decays without *CP* violation

Cabibbo−favoured decays (CF):

- no penguin contribution and no *CP* violation in the Standard Model
- used to check the detector effects (control decays)

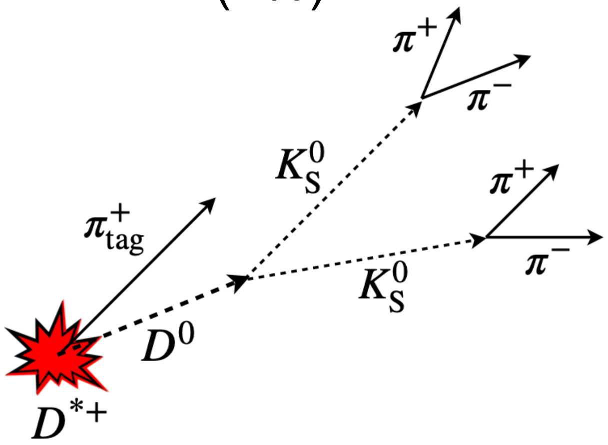


Doubly Cabibbo−suppressed decays (DCS):

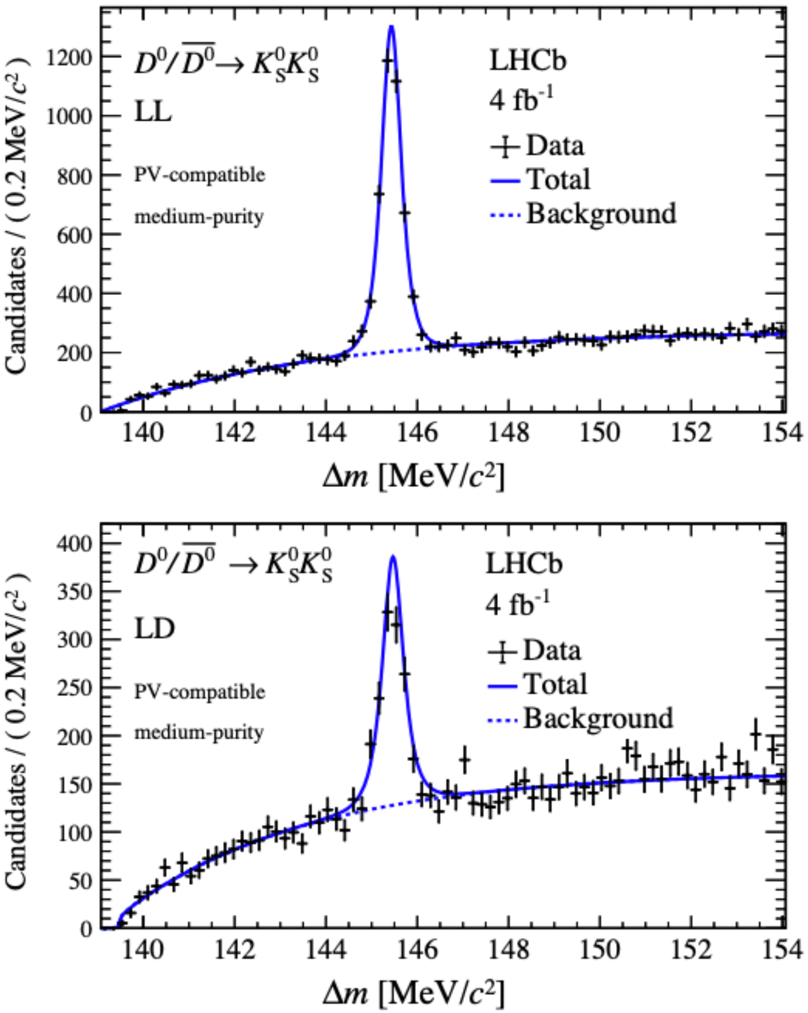
- no *CP* violation in the SM
- any signal of *CP* violation will mean new physics existence

Time integrated *CP* violation in $D^0 \to K^0_s K^0_s$

CPV enhanced to $\mathcal{O}(1\%)$!

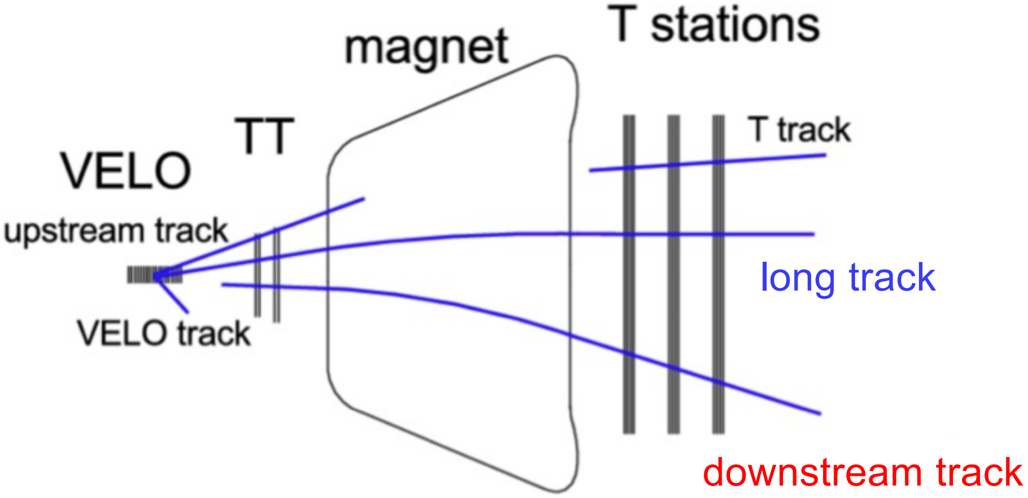


Phys. Rev. D104 (2021) L031102



Data (pairs of $K^0_s K^0_s$) are split according to different track types:

- long-long (LL)
- long-downstream (LD)



$$\Delta m = m(K^0_s K^0_s \pi^+_{\mathrm{tag}}) - m(K^0_s K^0_s)$$

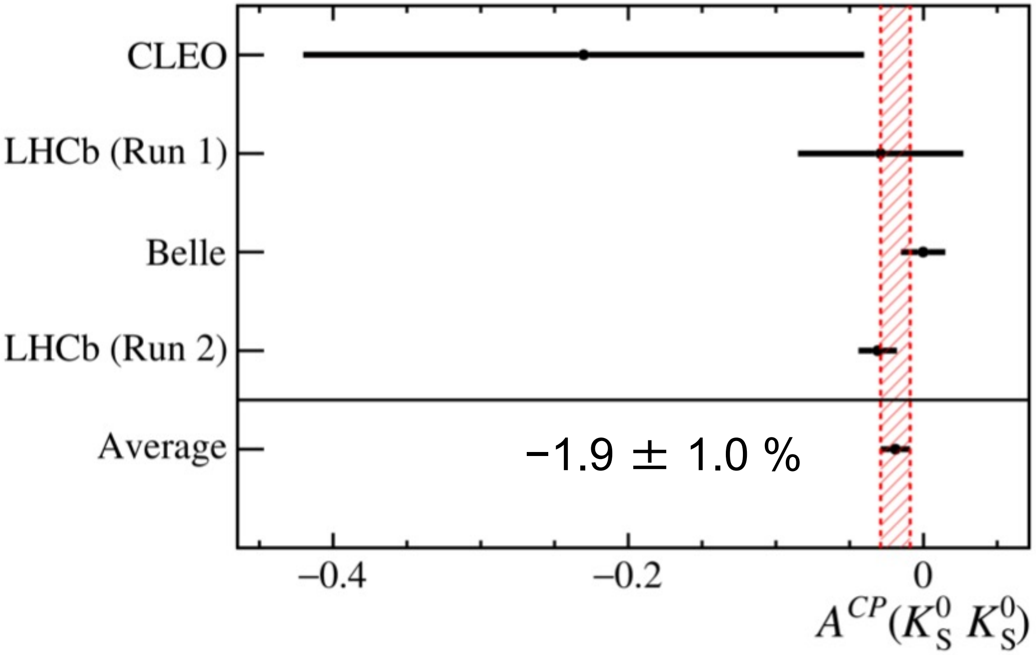
Time integrated *CP* violation in $D^0 \to K^0_s K^0_s$

Phys. Rev. D104 (2021) L031102

$$\boxed{A^{CP}(D^0 \to K^0_s K^0_s) = (-3.1 \pm 1.2^{(stat)} \pm 0.4^{(syst)} \pm 0.2^{(ext)})\%}$$

The (*ext*) error is due to the uncertainty on the *CP* violation of the calibration channel ($D^0 \to K^+K^-$)

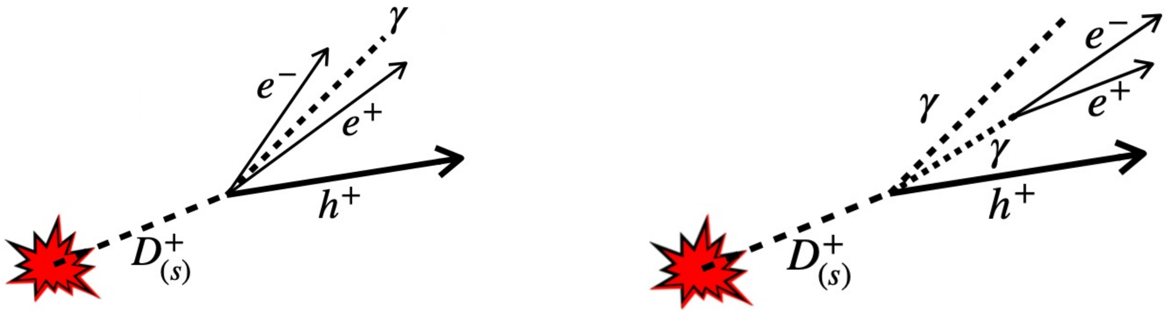
- Compatible with 0 at 2.4σ
- Statistically dominated
- This is the most precise determination of this quantity to date



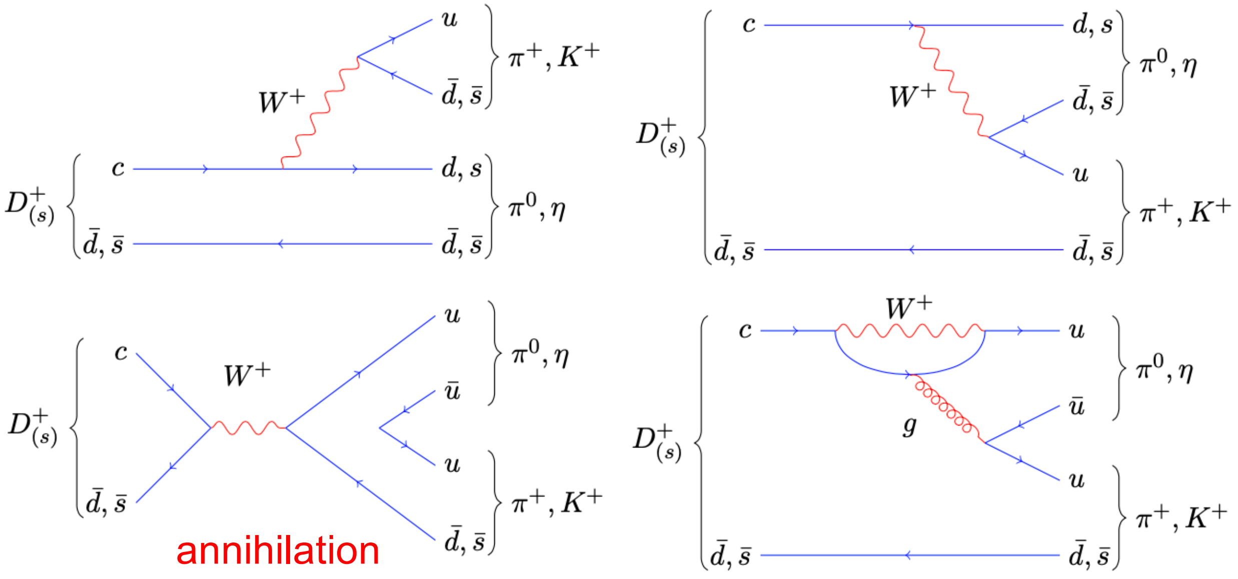
Time integrated *CP* violation in $D^+_{(s)} \rightarrow h^+h^0$

There are seven charged D^+ meson decays that allow to test of direct *CP* violation in the decay amplitude

$D^+_{(s)} \rightarrow h^+\pi^0$, $h^+\eta$



h is K or π and the π^0 and η are reconstructed using the $e^+e^-\gamma$ final state (photon conversion $\gamma(\rightarrow e^+e^-)\gamma$ or Dalitz decay)



annihilation

SCS $D^+ \rightarrow \pi^+\pi^0$ is of interest:

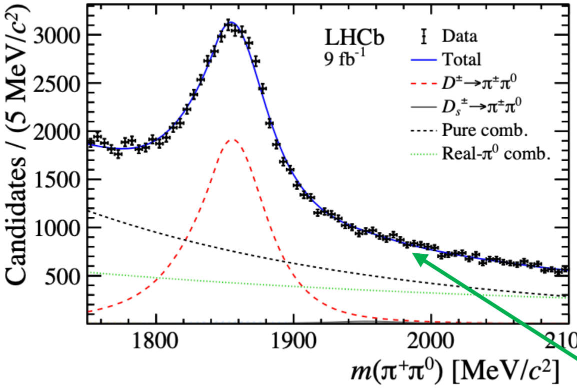
- CPV in the SM is expected to be zero as a result of isospin constraints
- would be an indication of physics beyond the SM

Time integrated *CP* violation in $D^+_{(s)} \to h^+h^0$

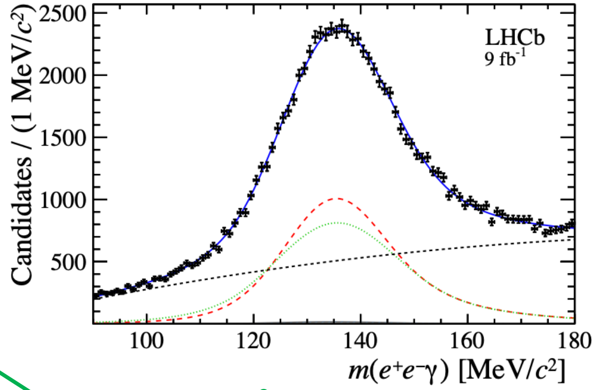
JHEP 06 (2021) 019

The $D^+ \to \pi^+\pi^0$ decay:
- nonzero CPV would be an indication of physics beyond the SM
- ~29k candidates

$D^+ \to \pi^+\pi^0$



$\pi^0 \to e^+e^-\gamma$

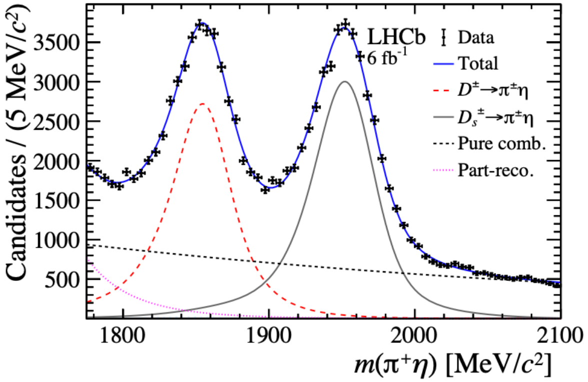


$D^+_s \to \pi^+\pi^0$

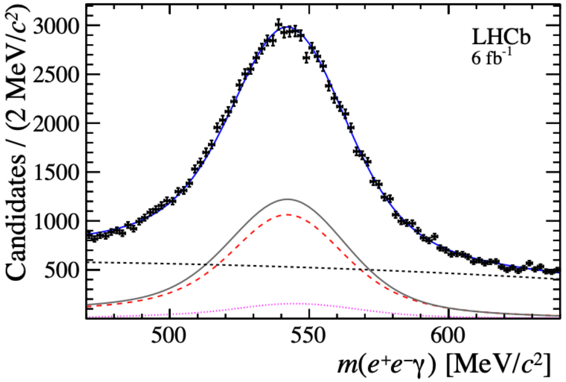
not seen

Mode		Yield	
	2011	2012	Run 2
$D^+ \to \pi^+\pi^0$	740 ± 60	$2\,240 \pm 120$	$25\,750 \pm 430$
$D^+_s \to \pi^+\pi^0$	20 ± 30	-50 ± 50	450 ± 120
$D^+ \to K^+\pi^0$	10 ± 13	90 ± 30	$2\,440 \pm 110$
$D^+_s \to K^+\pi^0$	54 ± 13	150 ± 30	$2\,580 \pm 90$
$D^+ \to \pi^+\eta$	-	-	$32\,760 \pm 380$
$D^+_s \to \pi^+\eta$	-	-	$37\,950 \pm 340$
$D^+ \to K^+\eta$	-	-	880 ± 70
$D^+_s \to K^+\eta$	-	-	$2\,520 \pm 70$

$D^+_{(s)} \to \pi^+\eta$



$\eta \to e^+e^-\gamma$



Time integrated *CP* violation in $D^{+}_{(s)} \rightarrow h^{+}h^{0}$

LHCb results, JHEP 06 (2021) 019

$\mathcal{A}_{CP}(D^{+} \rightarrow \pi^{+}\pi^{0}) = (-1.3 \pm 0.9 \pm 0.6)\%$ SCS

$\mathcal{A}_{CP}(D^{+} \rightarrow K^{+}\pi^{0}) = (-3.2 \pm 4.7 \pm 2.1)\%$ DCS

$\mathcal{A}_{CP}(D^{+} \rightarrow \pi^{+}\eta) = (-0.2 \pm 0.8 \pm 0.4)\%$ SCS

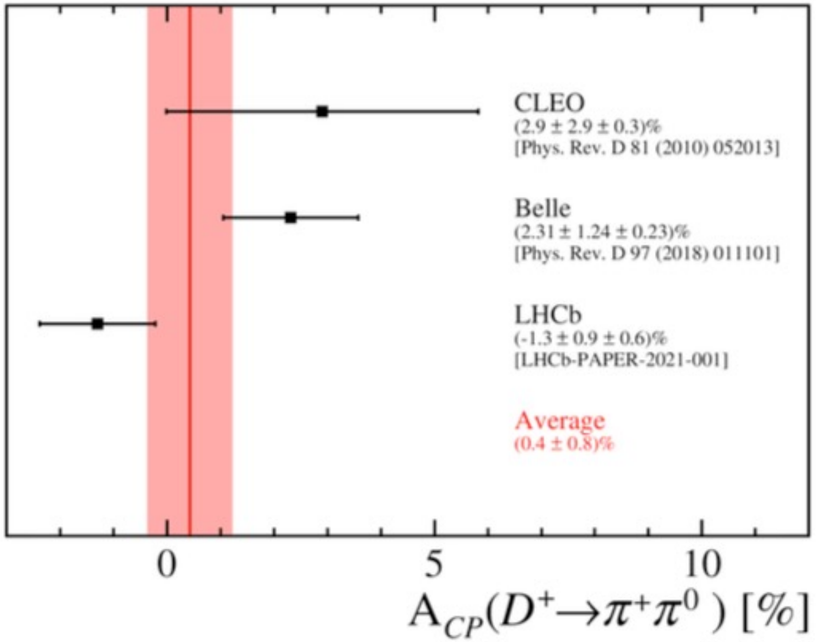
$\mathcal{A}_{CP}(D^{+} \rightarrow K^{+}\eta) = (-6 \pm 10 \pm 4)\%$ DCS

$\mathcal{A}_{CP}(D^{+}_{s} \rightarrow K^{+}\pi^{0}) = (-0.8 \pm 3.9 \pm 1.2)\%$ SCS

$\mathcal{A}_{CP}(D^{+}_{s} \rightarrow \pi^{+}\eta) = (0.8 \pm 0.7 \pm 0.5)\%$ CF

$\mathcal{A}_{CP}(D^{+}_{s} \rightarrow K^{+}\eta) = (0.9 \pm 3.7 \pm 1.1)\%$ SCS

Results in $D^{+} \rightarrow \pi^{+}\pi^{0}$



- These results are consistent with no *CP* violation and mostly constitute the most precise measurements of A_{CP} in these decay modes to date
- Belle reported concurrent measurements (Phys. Rev. D103 (2021) 112005)

$$\mathcal{A}_{CP}(D^{+}_{s} \rightarrow K^{+}\pi^{0}) = 0.064 \pm 0.044 \pm 0.011$$
$$\mathcal{A}_{CP}(D^{+}_{s} \rightarrow K^{+}\eta) = 0.021 \pm 0.021 \pm 0.004$$
$$\mathcal{A}_{CP}(D^{+}_{s} \rightarrow \pi^{+}\eta) = 0.002 \pm 0.003 \pm 0.003$$

In agreement with the LHCb

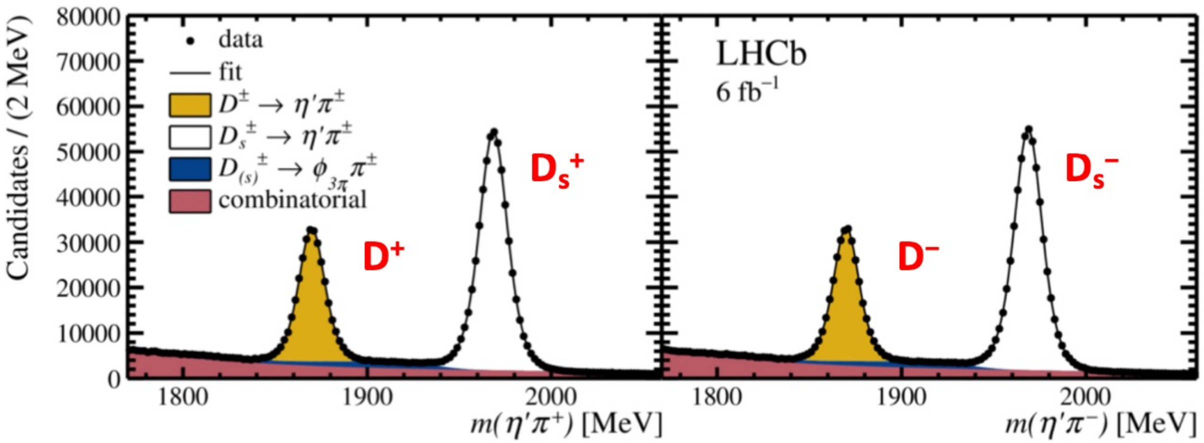
CP violation in $D^+_{(s)} \to \eta^{(\prime)}\pi^+$

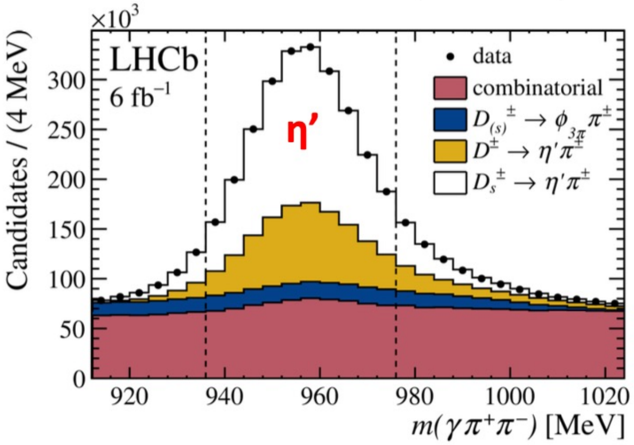
arXiv: 2204.12228 (submitted to JHEP)

$D^{\pm}_{(s)} \to \eta^{(\prime)}\pi^{\pm}$, where $\eta^{(\prime)} \to \pi^+\pi^-\gamma$

CP asymmetries are obtained from simultaneous fits to $m(\pi^+\pi^-\gamma)$ and $m(\eta^{(\prime)}\pi^{\pm})$

0.55M of $D^{\pm}\to\eta'\pi^{\pm}$, 1M of $D^{\pm}_s\to\eta'\pi^{\pm}$





$$\mathcal{A}^{CP}(D^+\to\eta\pi^+) = (0.34\pm0.66\pm0.16\pm0.05)\%,$$

$$\mathcal{A}^{CP}(D_s^+\to\eta\pi^+) = (0.32\pm0.51\pm0.12)\%,$$

$$\mathcal{A}^{CP}(D^+\to\eta'\pi^+) = (0.49\pm0.18\pm0.06\pm0.05)\%,$$

$$\mathcal{A}^{CP}(D_s^+\to\eta'\pi^+) = (0.01\pm0.12\pm0.08)\%,$$

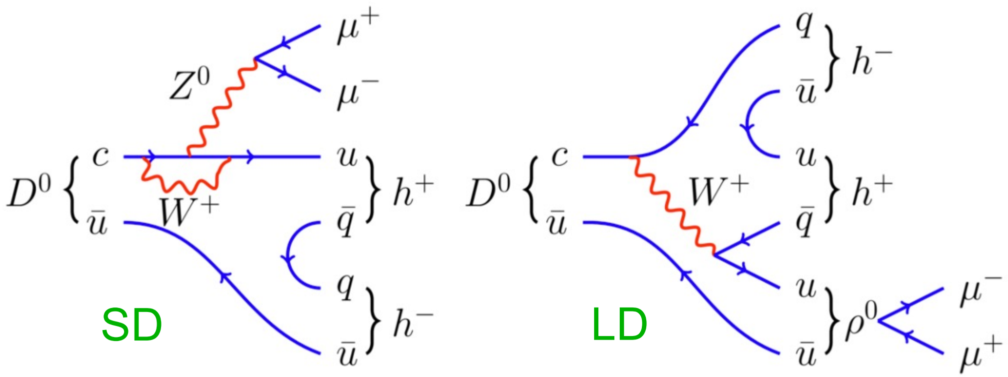
- Results are consistent with *CP* symmetry
- Statistical uncertainties dominate
- The most precise measurements up to date

CP violation in $D^0 \to h^+h^-\mu^+\mu^-$

Very rare charm decays

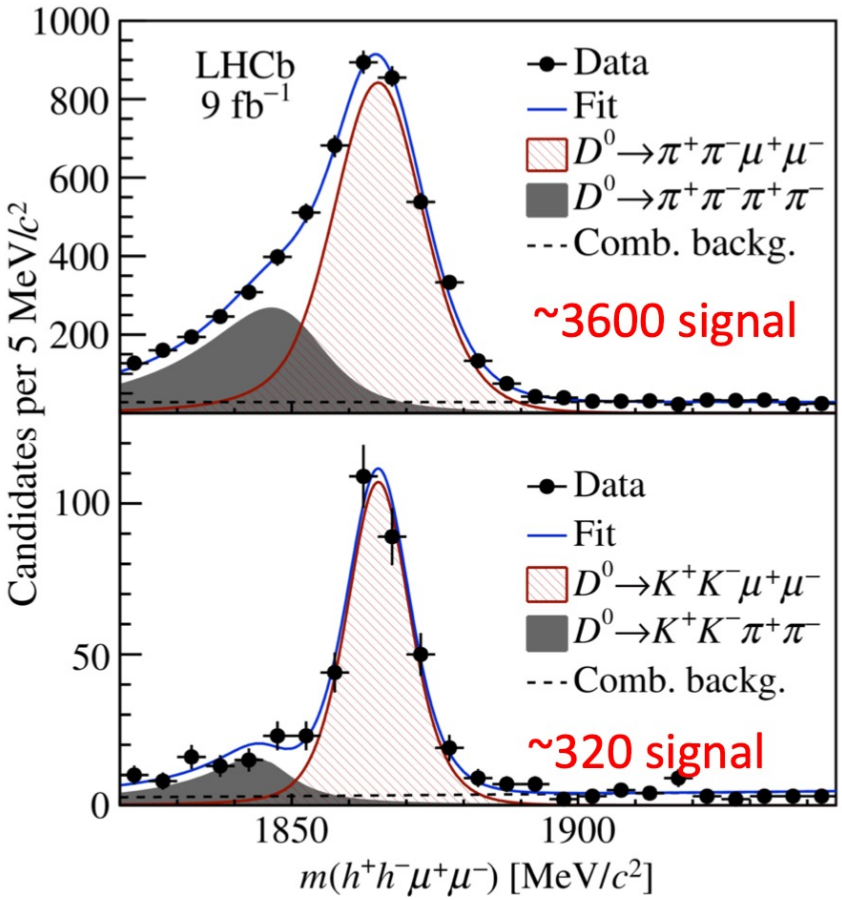
$D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$

proceed via $c \to u\,\mu^+\mu^-$ FCNC processes



- Sensitive to new physics through interference of short-distance (SD) and long-distance (LD) contributions
- First full angular analysis is conducted to search for the CP asymmetries

Phys.Rev.Lett.128 (2022) 221801



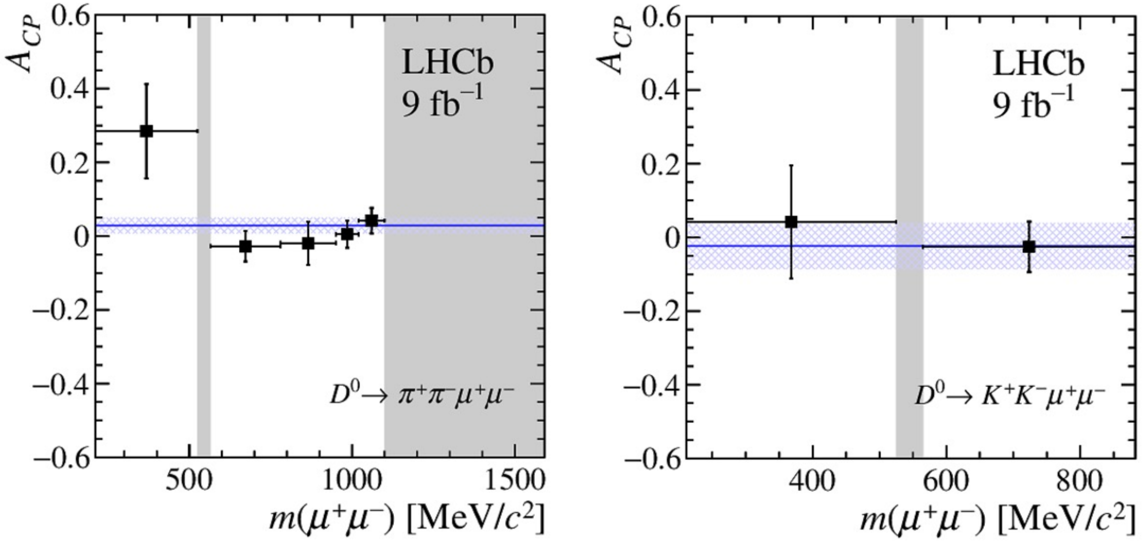
~3600 signal

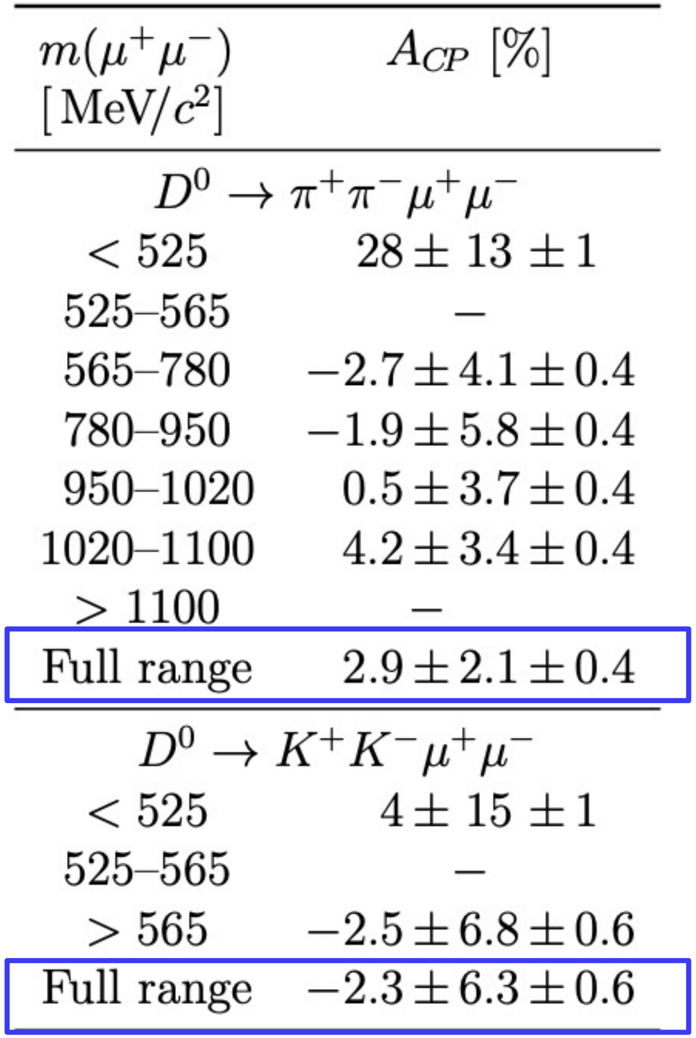
~320 signal

CP violation in $D^0 \to h^+h^-\mu^+\mu^-$

Phys.Rev.Lett.128 (2022) 221801

Measured overall *CP* asymmetries A_{CP} in the dimuon-mass regions





$m(\mu^+\mu^-)$ [MeV/c^2]	A_{CP} [%]
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	
< 525	$28 \pm 13 \pm 1$
525–565	–
565–780	$-2.7 \pm 4.1 \pm 0.4$
780–950	$-1.9 \pm 5.8 \pm 0.4$
950–1020	$0.5 \pm 3.7 \pm 0.4$
1020–1100	$4.2 \pm 3.4 \pm 0.4$
> 1100	–
Full range	$2.9 \pm 2.1 \pm 0.4$
$D^0 \to K^+K^-\mu^+\mu^-$	
< 525	$4 \pm 15 \pm 1$
525–565	–
> 565	$-2.5 \pm 6.8 \pm 0.6$
Full range	$-2.3 \pm 6.3 \pm 0.6$

- All measurements are consistent with the SM predictions (where present) and *CP* symmetry
- Statistically dominated

Summary

- So far, *CP* violation in the charm sector is confirmed only in the difference of asymmetries between $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ (PRL 122 (2019) 211803)

- In all other charm meson decays, results are consistent with *CP* symmetry
  - statistical uncertainties dominate
  - increasing data statistics will allow to test the SM in more details

- Is there new physics ?
  We cannot confirm, but we cannot deny it

- The LHCb upgrade (started in 2019) has almost finished. From April 2022, our detector is on (Run 3).

- The goal is to reach ~23/fb (Run 3) and ~50/fb (Run 4) (Run 1+2: ~9/fb)

- Breaking news: ~3/fb got it till today ☺ ☺ ☺

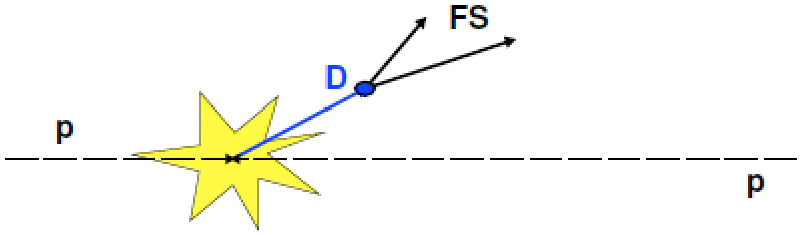
Back up

Charm particle production at LHCb

Two production types (statistically independent):

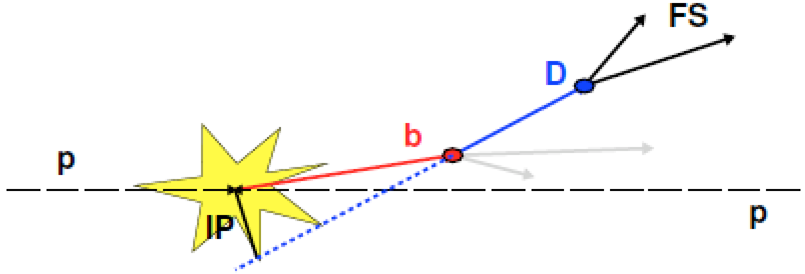
1. prompt – produced directly in the primary vertex (pp collision)

IP ~ 0



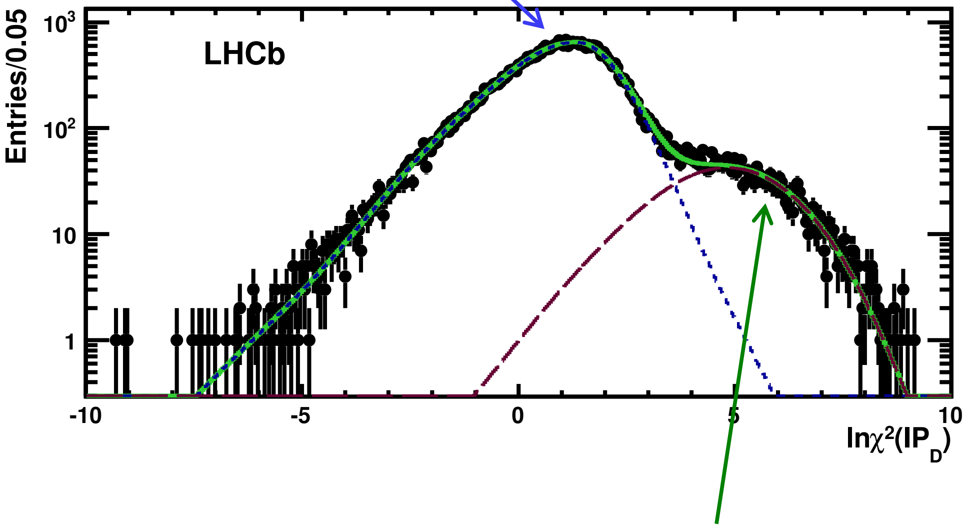
2. secondary – produced in *B*, Λ_b ,… decays $B \to DX$, $\Lambda_b \to \Xi_c X$,… (yield ~1/6)

IP > 0



prompt

JHEP04(2012)129



secondary

IP – impact parameter wrt. the primary vertex

The D^0 flavour tagging

Flavour cannot be inferred from the final state if this is shared by D^0 and anti-D^0

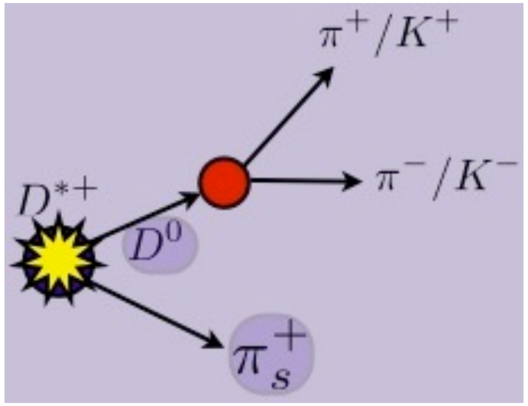
The LHCb uses two methods to identify D^0 flavour at the production state

1. pion-tagged method
   the sign of slow pion from D^* decays is used to tag the initial D^0 flavour

   $D^{*+} \rightarrow D^0 \pi^+_s$

   $D^{*-} \rightarrow$ anti-$D^0 \pi^-_s$

prompt D^0

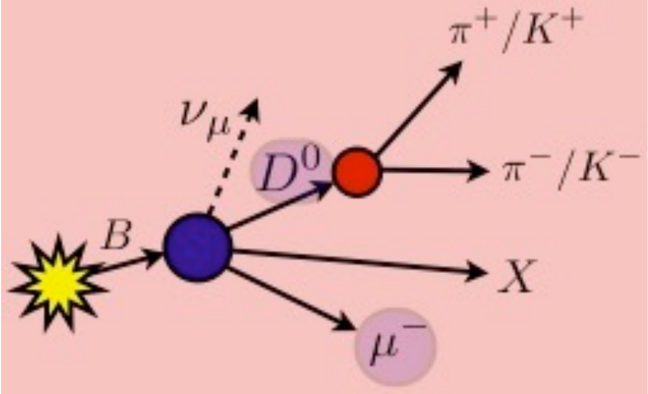


2. muon-tagged method (yield ~1/6)
   the sign of muon from semileptonic B decays is used to tag D^0 flavour

   $B^- \rightarrow D^0 \mu^- \nu_\mu X$

   $B^+ \rightarrow$ anti-$D^0 \mu^+ \nu_\mu X$

secondary D^0



The Standard Model predictions for charm

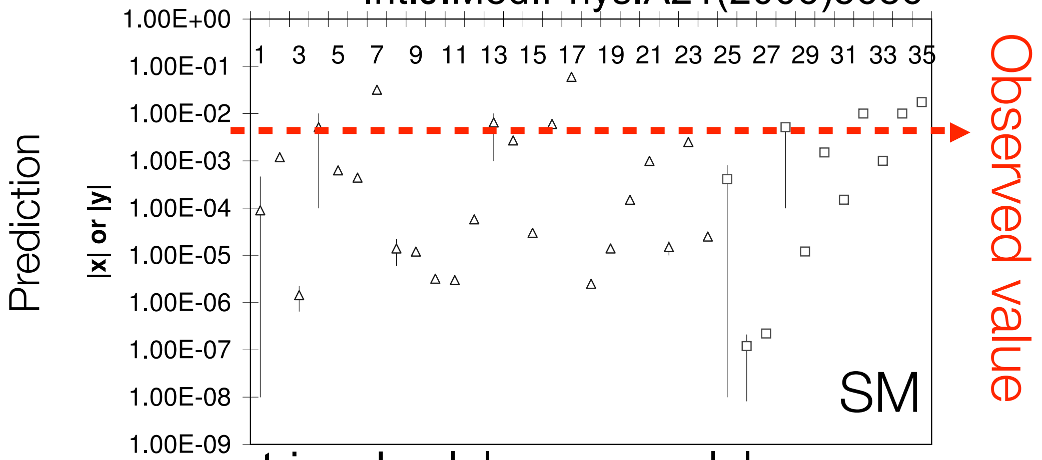
- Predicted CPV in charm sector is very small $\lesssim 10^{-4} - 10^{-3}$ (much smaller than measured in the beauty sector)

- The SM predictions vary widely

- New physics contributions can enhance CPV up to 10^{-2}

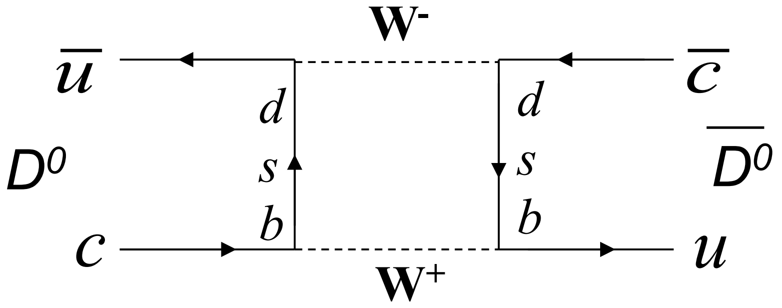
  Int.J.Mod.Phys.A21(2006)5381 ;
  Ann.Rev.Nucl.Part.Sci.58(2008)249

Int.J.Mod.Phys.A21(2006)5686

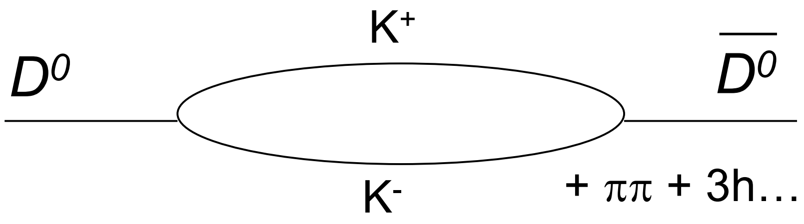


triangles |x| ; squares |y|

x ~ y < 1%



Mixing via box diagram, short range



+ rescattering (new issue)

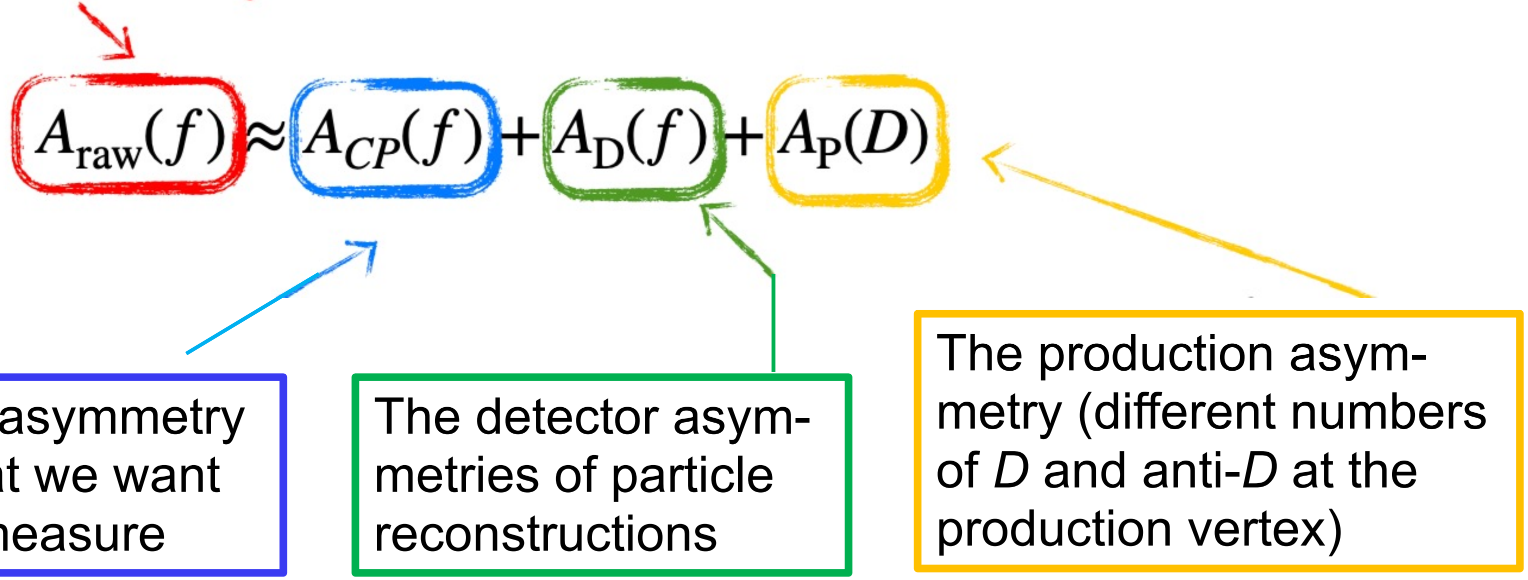
Mixing via hadronic intermediate states, long range (difficult to calculate)

Measuring *CP* asymmetry

- The $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays are used to measure the time integrated *CP* violation

- The measured raw asymmetry A_{raw} may be written as a sum of components that are physics and detector effects:

$$A_{\mathrm{raw}}(f) = \frac{N(D \rightarrow f) - N(\bar{D} \rightarrow \bar{f})}{N(D \rightarrow f) + N(\bar{D} \rightarrow \bar{f})}$$



$$\boxed{A_{\mathrm{raw}}(f)} \approx \boxed{A_{CP}(f)} + \boxed{A_{\mathrm{D}}(f)} + \boxed{A_{\mathrm{P}}(D)}$$

CP asymmetry what we want to measure

The detector asymmetries of particle reconstructions

The production asymmetry (different numbers of *D* and anti-*D* at the production vertex)

The A_{raw}, A_{D} and A_{P} are order ~2% or smaller but A_{CP} is smaller than 10^{-3}

The first observation of *CP* violation in charm

The detector asymmetries for K^-K^+ and $\pi^-\pi^+$ cancel since the final states are charge symmetric and the A_P is independent of the final state and this term cancels in the first order if we subtract raw asymmetries

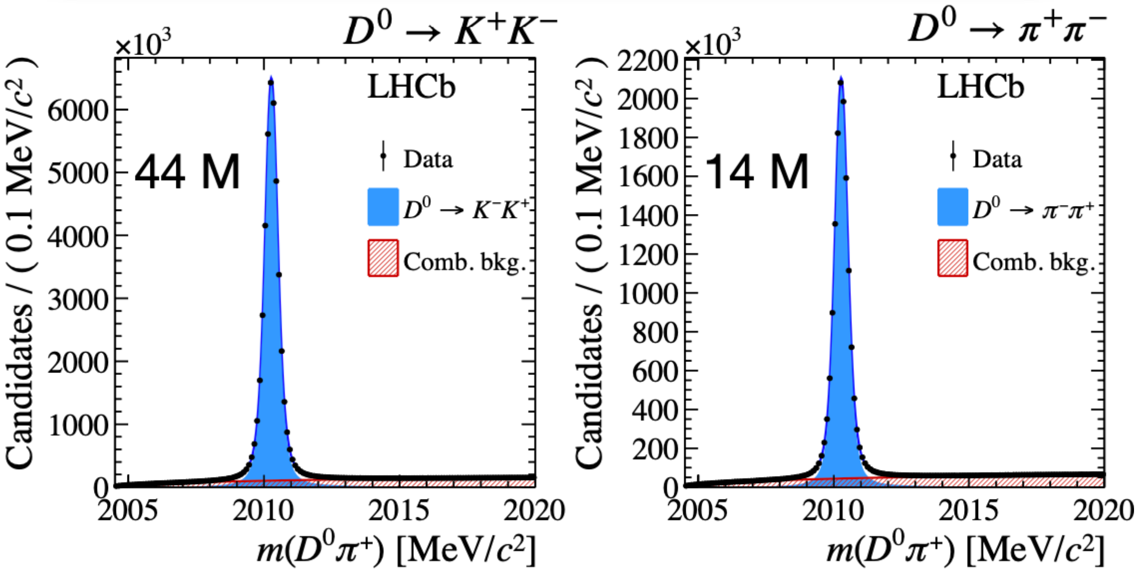
$$\boxed{\begin{aligned}&A_{\text{raw}}(K^+K^-) - A_{\text{raw}}(\pi^+\pi^-) = \\ &= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \equiv \Delta A_{CP} = (-1.54 \pm 0.29)\cdot 10^{-3}\end{aligned}}$$

(5.3σ)

PRL 122 (2019) 211803

$$\Delta A_{CP} = [a_{CP}^{dir}(K^-K^+) - a_{CP}^{dir}(\pi^-\pi^+)] + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{ind}$$

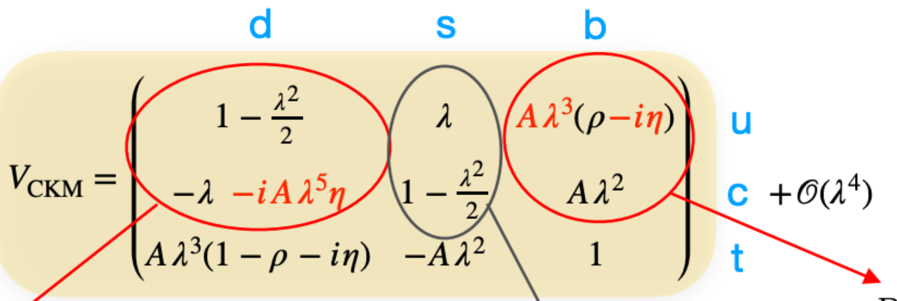
[JHEP 1106 (2011) 089]



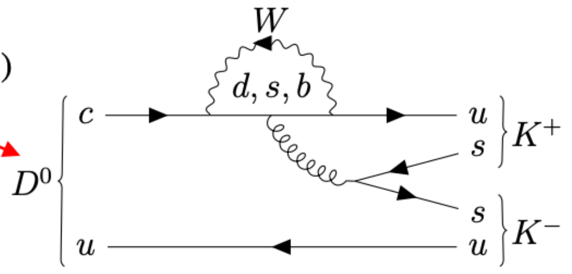
- 2015-2018, 5.7/fb
- Direct (majority) and indirect *CP* asymmetries contribute
- Indirect CP asymmetry is smaller than 10%

Re-scattering contribution

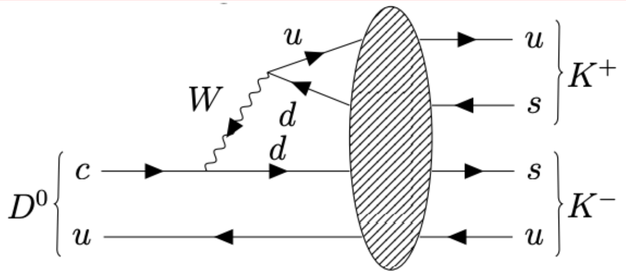
In the Standard Model, *CP* violation is expected to be detectable only in singly Cabibbo-supressed decays



$$V_{\mathrm{CKM}} = \begin{array}{c|ccc|c} & d & s & b & \\ \hline & 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) & u \\ & -\lambda \ -iA\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 & c \\ & A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 & t \end{array} + \mathcal{O}(\lambda^4)$$

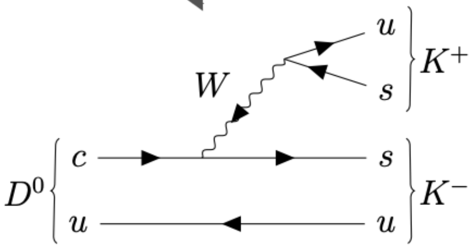


QCD penguin



Re-scattering: d anti-d → s anti-s

It may be more important than we thought previously



Tree

Re-scattering following a tree level amplitude and *CP* violation follows from tiny nonunitary of 2 x 2 CKM submatrix